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# Scalp-Implantable MIMO Antenna for High-Data-Rate Head Implants

Amjad Iqbal, *Member, IEEE*, Muath Al-Hasan, *Senior Member, IEEE*, Ismail Ben Mabrouk, *Senior Member, IEEE*, and Mourad Nedil, *Senior Member, IEEE*

**Abstract**—A quad-element multiple-input multiple-output (MIMO) antenna is designed at 433 MHz Industrial, Scientific, and Medical (ISM) band, to increase the transmission data-rate and minimize the multipath fading. The proposed MIMO antenna consists of semi-circular meandered radiators with a shared ground. It is designed and optimized inside an implantable medical device (IMD) in a human head model. The antenna's results show a 10-dB fractional bandwidth (FBW) of 38.26% (355–523 MHz) with a peak realized gain of -28.3 dBi. A high isolation ( $> 32.6$  dB) between MIMO elements is obtained using a central metallic via. Specific absorption rate (SAR) and link budget are analyzed to validate the effectiveness of this antenna. The  $4 \times 4$  MIMO channel parameters are calculated and validated. Furthermore, this antenna provides a channel capacity of 19.9 bps/Hz which is about three times higher than the single-input single-output (SISO) configuration of  $\approx 5.89$  bps/Hz. Hence, this MIMO configuration is a promising candidate for high-data-rate head implants.

**Index Terms**—MIMO antenna, implantable medical devices, implantable antenna, coupling coefficient, mutual coupling.

## I. INTRODUCTION

RECENTLY, IMDs have gained substantial focus of biomedical engineers due to wide range of applications in medical and healthcare industry [1]–[2]. This is due to the fact that an IMD collects useful information from the user to transfer it to an outside transceiver [3]–[4]. Although an antenna is an important component of an IMD, however, the large space occupied by it is considered as an issue for compact biomedical devices [5]–[6]. Consequently, the IMD's size mainly depends on the antenna's geometry [7]–[8]. Moreover, a reliable communication link with an external receiver is paramount for IMDs [9]–[10]. Therefore, IMDs with low latency and high reliability are desired [11]–[12]. Thus, implantable antennas should have higher gains, stable radiation patterns, and efficient wireless communication links. In fact, designing such antennas inside the human body is still a challenging task due to number of issues, such as biocompatibility, impedance matching, wide bandwidth, size

restriction, human safety, and reliable communication link with an external device [11]–[13].

In this context, several implantable antennas have been suggested using single-input single-output (SISO) configurations [14]. However, current SISO antennas cannot satisfy the needs of modern IMDs due to their limited data-rate and low spectral efficiency [15]. Hence, few MIMO antenna systems have been proposed to solve the problems of SISO configurations. In [16], a dual-port MIMO antenna, based on a spiral resonator and a capacitor, is reported to transfer real-time high-resolution images from capsule endoscope to an external device. It operates at 433 MHz with an FBW of only 3.2% and large dimensions of  $120 \text{ mm}^3$ . In [17], a quad-port meandered antenna, combined with metamaterial, is introduced to maintain high isolation. This antenna has an FBW of 18.64% and occupies large volume of  $434.6 \text{ mm}^3$ . In [18], a spiral resonator is adopted to design a dual-port MIMO antenna at 403 MHz Medical Device Radiocommunication Service (MedRadio) band with an adequate FBW of 35.9% and isolation of 25.6 dB. This antenna occupies large dimensions of  $307 \text{ mm}^3$ . In [19], two-element single band antenna is designed. In this design, metallic vias are used for miniaturization and neutralization line is adopted to increase isolation. Consequently, it operates with an isolation = 37 dB and FBW = 8.5%. In [20]–[21], non-planar implantable MIMO antennas are reported; however, their non-planar and large geometry restricts their applications in compact IMDs. In fact, the majority of the suggested implantable MIMO antennas have large dimensions with narrow bandwidths.

To address the aforementioned limitations, a compact and low profile quad-port implantable antenna is proposed. The compactness is achieved using a semi-circular meandered geometry, while isolation between the elements is enhanced through a central metallic via. Consequently, it has dimensions of  $23.69 \text{ mm}^3$  and isolation of  $> 32.6$  dB. Furthermore, it has a wide bandwidth of 38.26% (355–523 MHz) and peak realized gain of -28.3 dBi. The advantages of the proposed prototype are 1) compact and low profile, 2) highly uncorrelated MIMO channels, 3) wide operating bandwidth, and 4) high channel capacity.

## II. IMPLANTABLE MIMO ANTENNA DESIGN

The geometry of the proposed four-port implantable MIMO antenna is shown in Fig. 1. Each radiator is composed of semi-circular shaped meandered radiator, excited by a 50 $\Omega$  coaxial probe. A high dielectric constant laminate RO3010 ( $\epsilon_r$ ,

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A. Iqbal and I. Ben Mabrouk are with the Department of Engineering, Durham University, Durham DH1 3LE, UK (e-mail: aiqbal@ieee.org, ismail.benmabrouk@durham.ac.uk).

M. Al-Hasan is with the Network and Communications Engineering Department, Al Ain University, Al Ain, United Arab Emirates (e-mail: muath.alhasan@aau.ac.ae).

M. Nedil is with the Communications Research Laboratory (LRTCS), University of Quebec at Abitibi-Temiscamingue (UQAT), Val-d'Or, QC J9P 1Y3, Canada (e-mail: mourad.nedil@uqat.ca).



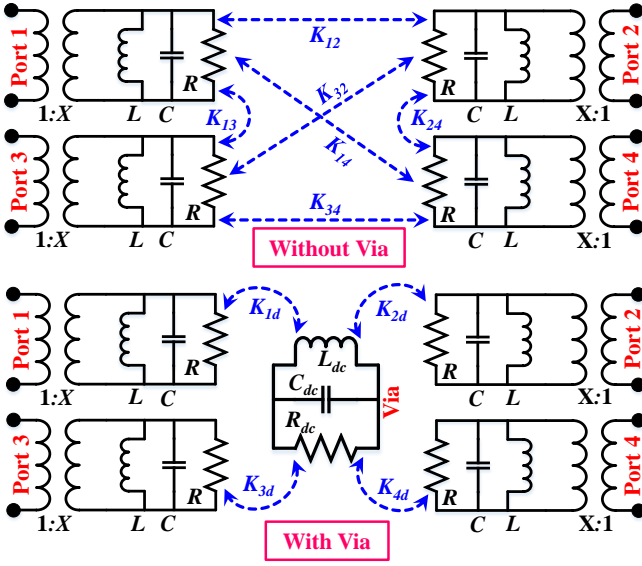


Fig. 5: Equivalent circuit model of quad-element MIMO antenna system ( $X = 1.1$ ,  $R = 43.25 \Omega$ ,  $L = 7.68 \text{ nH}$ ,  $C = 16.3 \text{ pF}$ ,  $R_{dc} = 149.3 \Omega$ ,  $L_{dc} = 0.98 \text{ nH}$ ,  $C_{dc} = 4.2 \text{ pF}$ ,  $K_{12} = 0.09$ ,  $K_{13} = 0.10$ ,  $K_{14} = 0.07$ ,  $K_{23} = 0.09$ ,  $K_{24} = 0.08$ ,  $K_{34} = 0.11$ ,  $K_{1d} = 3$ ,  $K_{2d} = 1.38$ ,  $K_{3d} = 2.8$ , and  $K_{4d} = 1.33$ ).

all resonators are directly coupled with the decoupling circuit ( $R_{dc}$ ,  $L_{dc}$ , and  $C_{dc}$ ). Therefore, the coupling level between antenna elements is reduced. Hence, isolation between antenna elements is increased. The optimized circuit values are given in the caption of Fig. 5. The S-parameters of the circuit model are compared with the EM model and the fabricated model, as shown in Fig. 6.

### III. RESULTS AND DISCUSSIONS

This antenna is initially designed in a cubical skin phantom to reduce the computational complexity. Later, it is integrated in a flat-type device and optimized inside a realistic human head model. Then, an accurate circuit model is developed to validate the concept. Finally, the antenna is fabricated on the Rogers RO3010 substrate and integrated in a flat-type biocompatible alumina ( $\epsilon_r = 9.8$ ) device, as shown in Fig. 2. Furthermore, 3D printing technology is used to fabricate the casing of the flat-type device. Then, the antenna prototype along with other IMD components are placed inside the device, where the lid is closed using epoxy. Afterwards, the flat-type device is placed inside minced pork meat for practical measurements. The S-parameters measurements are performed by connecting two ports of the antenna to the network analyzer and the rest of the ports are terminated with a  $50\Omega$  load. The measured  $S_{11}$  has the resonance at 435 MHz with a 10-dB bandwidth of 40.35% (356-536 MHz) and isolation ( $S_{21}$ ) of more than 37 dB, as shown in Fig. 6. The radiation patterns and gain of the antenna at 433 MHz are also measured. While measuring the radiation patterns, only one port is attached to the analyzer and all others are terminated with a  $50\Omega$  load. A high-gain horn antenna is used as a transmitting antenna and is placed 3 meters away from the proposed antenna. The horn

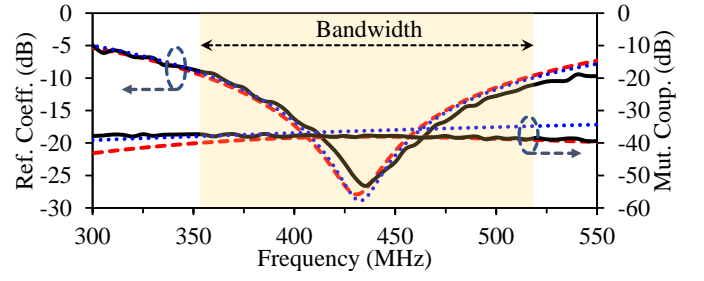


Fig. 6: S-parameters of the EM model (dashed line), equivalent circuit model (dotted line), and fabricated prototype (solid line).

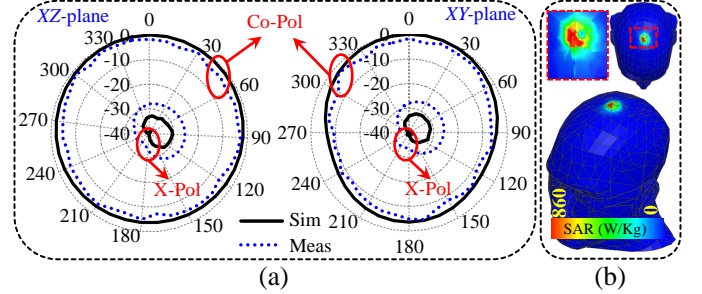


Fig. 7: (a) Normalized radiation patterns (XZ- and YZ-plane) of the antenna at 433 MHz. (b) 10-g SAR at 433 MHz for 1 W input power.

antenna has a width = 49 cm, height = 32 cm and depth = 40 cm. It can be observed from Fig. 7a that the proposed antenna has nearly omni-directional radiation pattern. It is worth mentioning that omni-directional radiation patterns are highly desired for biomedical implants due to their ability to transmit and receive signal from all directions. At 433 MHz, the simulated and measured peak realized gain of the antenna is -28.3 dBi and -30.1 dBi, respectively. Moreover, it has a radiation efficiency of -34.5 dB at 433 MHz.

Input power and specific absorption rate (SAR) are important factors to ensure human safety. In fact, peak SAR value should be lower than 2 W/kg (averaged over a 10-g of tissue) for an input power of 1 W. When all antenna's elements are excited with 1 W of input power, a peak SAR value of 860 W/Kg is observed, as illustrated in Fig. 7b. In fact, each element of the antenna contributes 215 W/Kg to the total SAR value. According to IEEE C95.1-2019, the proposed antenna can support input power up to 9.3 mW for a safe operation. In practical applications, a maximum power of -16 dBm (ITU-R RS.1346) is allowed for implants to avoid interference with other devices [24]. Therefore, the proposed antenna is even safe for an input power of 9.68 dBm (9.3 mW).

Moreover, a robust communication link is important to exchange the information between the implant and external device. Therefore, a link margin ( $LM \text{ [dB]} = P_a - P_r$ ) is calculated based on Equations (1)-(2) [17]. The link margin is calculated using different data-rates at 433 MHz, as illustrated in Fig. 8. Considering at least 20 dB link margin, the proposed implantable MIMO antenna can successfully transmit the data over 25 meters at 78 Mbps.

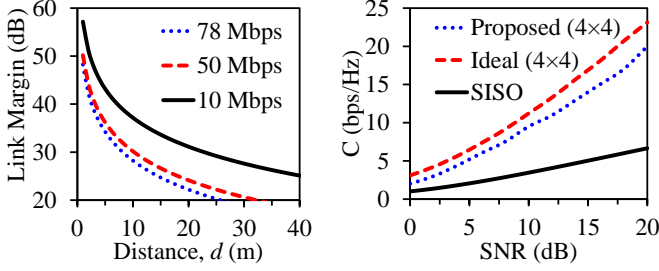


Fig. 8: Calculated link margins and channel capacities.

$$P_a[dB] = P_t + G_t + G_r - 10\log_{10}(4\pi d/\lambda)^2 - N_o \quad (1)$$

$$P_r[dB] = E_b/N_o + 10\log_{10}(B_r) + G_d \quad (2)$$

where,  $P_t = -16$  dBm is the transmitted power,  $G_t = -28.3$  dBi is the transmitting antenna gain,  $G_r = 2$  dBi is the receiving antenna gain,  $\lambda$  is the wavelength at 433 MHz,  $d$  is the distance between the receiving and transmitting antennas,  $N_o = -199.5$  dB/Hz is the noise power density,  $E_b/N_o = 9.6$  dB is the ideal PSK,  $B_r$  is the bit rate, and  $G_d = 2.5$  dB is the fixing deterioration.

#### A. MIMO Channel Parameters

The main advantage of the MIMO antenna is its high channel capacity without additional bandwidth and power. Ideally, the channel capacity of the uncorrelated MIMO system increases with more antennas. But in practical applications, one cannot achieve uncorrelated channels. The channel capacity of  $N \times N$  MIMO antenna system is calculated using Equation (3) [29].

$$CC = \log_2(\det[I + (SNR/N)HH^*]) \quad (3)$$

where  $CC$  is the channel capacity,  $SNR$  expresses the signal to noise ratio,  $H$  is the channel matrix and is calculated from the radiation patterns of the antenna,  $I$  is the identity matrix, and  $H^*$  is the conjugate of  $H$  matrix. In fact,  $H$  matrix contains the gain and phase information of MIMO elements. The channel matrix ( $H$ ) is calculated using standard equations of [30], [31]. The calculated channel capacity as a function of SNR values is shown in Fig. 8. It can be observed that the channel capacity of the proposed MIMO antenna is higher than SISO configuration under similar conditions. Considering  $SNR = 20$  dB, the proposed antenna has channel capacity of 19.9 bps/Hz; which is almost three times higher than the SISO configuration of  $\approx 5.89$  bps/Hz [32]. Hence, this antenna is a promising candidate for high-data-rate head implants.

The Envelop Correlation Coefficient (ECC) is a vital MIMO channel parameter, which characterizes the dependency of MIMO elements. The ECC of the MIMO antenna system can be determined from S-parameters [33] or far-fields [34]–[35]. In our study, far-field patterns are used to calculate the ECC [35]. In fact,  $ECC < 0.5$  is considered as a fair value for high channel capacity [36]. It can be observed from Fig. 9 that the ECC values are less than 0.1 in the overall frequency band.

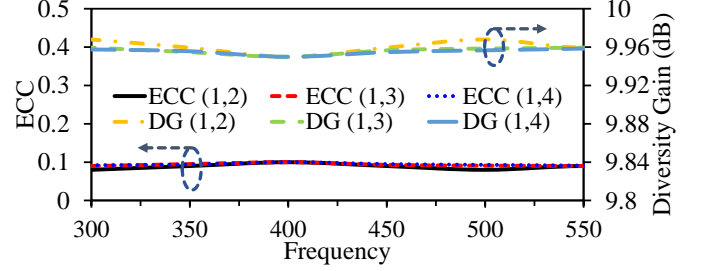


Fig. 9: Simulated ECC and DG of the implantable MIMO antenna system.

TABLE I: Comparison of the proposed implantable MIMO antenna with other implantable MIMO antennas.

Ref.	[16]	[17]	[18]	[19]	[20]	[21]	Proposed
Size (mm <sup>3</sup> )	120	434.6	307.3	280	3375	2879	<b>23.6</b>
Size ( $\lambda_g^3$ )	0.00002	0.003	0.000009	0.002	0.004	0.004	<b>0.0000019</b>
Tissue Layers	1	3	1	3	3	1	<b>Head model</b>
Elements	2	4	2	2	4	2	<b>4</b>
Freq. (GHz)	0.433	2.45	0.402	2.45	2.45, 5.8	2.46	<b>0.433</b>
BW (%)	3.2	18.64	35.9	8.5	36, 26	14.1	<b>38.26</b>
Isolation (dB)	12.17	15.9	25.6	37	32	30	<b>32.6</b>
ECC	NR	0.002	NR	NR	0.1	NR	<b>0.1</b>
DG (dB)	NR	NR	NR	NR	NR	NR	<b>9.95</b>
CC (bps/Hz)	NR	NR	NR	NR	NR	NR	<b>19.9@SNR = 20 dB</b>

BW: Bandwidth, Freq.: Frequency, NR: Not reported, SLS: System level study

Similarly, the Diversity Gain (DG) is another important parameter to assess a MIMO system, which has an inverse relationship with the ECC. A DG of 10 dB is expected for completely uncorrelated MIMO channels. The DG of the proposed MIMO antenna system is calculated using equation of [37]. The calculated DG of the antenna is higher than 9.95 dB in the entire operating band, as shown in Fig. 9.

In Table I, the performance of the proposed implantable MIMO antenna is compared with state-of-the-art implantable MIMO antennas. It can be observed that the proposed antenna has larger bandwidth and smaller dimensions compared to other implantable antennas. Furthermore, it has higher isolation than majority of the antennas. Moreover, important channel parameters, such as diversity gain and channel capacities are not fully reported in the previous studies.

#### IV. CONCLUSION

A compact and wideband quad-element MIMO antenna is developed for high-data-rate head implants. The MIMO antenna operates at 433 MHz ISM band with a 10-dB wide bandwidth of 38.26 % (355–523 MHz) and port isolation of more than 32.6 dB. The compact dimensions of  $13.5 \times 13.5 \times 0.13$  mm<sup>3</sup> ( $0.062\lambda_g \times 0.062\lambda_g \times 0.0005\lambda_g$ ) are achieved using a semi-circular meandered geometry, while isolation is enhanced through the central metallic via. This antenna is validated, considering it in a flat-device, in a realistic human head model, and minced pork meat. The MIMO channel parameters such as ECC, DG, and channel capacity are calculated which show promising results.



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